ENVIRONMENTAL EFFECTS ON THE STABILITY OF OPTICAL FIBERS USED FOR REFERENCE FREQUENCY DISTRIBUTION[1]

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BIOGRAPHIES

Malcolm Calhoun, a Member of the Technical Staff at Jet Propulsion Laboratory (JPL), has been working with fiber optics as a distribution medium for the Frequency and Time Systems Engineering group at JPL for the past four years. He holds the PhD degree in Electrical Engineering from Mississippi State University.

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ABSTRACT

The Frequency Standards Laboratory at the Jet Propulsion Laboratory (JPL) is responsible for the generation and distribution of ultra-stable reference frequencies in NASA's Deep Space Network (DSN). Certain assemblies and components of the Radio Science and VLBI systems are located in the cones of tracking antennas hundreds of meters from the Frequency and Timing Subsystem's frequency standards. Until recently, signals from the hydrogen maser frequency standards to the antennas were distributed via coaxial cables which are particularly sensitive to temperature variations as well as magnetic fields. The distribution design described in this paper is based on optical fibers which are less susceptible to environmental effects than are coaxial cables.

The temperature profile from the earth's surface to a depth of six feet over a time period of six months was used to optimize the placement of the fiber optic cables. In-situ evaluation of the fiber optic link performance indicates Allan deviation on the order of parts in 10^{16} at 1000 seconds averaging time; thus, the stability of the link is not degraded by environmental conditions. Optical fibers and electro-optic devices as distribution media appear to maintain hydrogen maser stability at the antenna location.

INTRODUCTION

The Frequency and Time Systems Engineering Group at the Jet Propulsion Laboratory (JPL) is responsible for the implementation of stable reference frequency sources and the distribution of time and frequency signals in the NASA Deep Space Network (DSN). The source of the reference signal typically is a hydrogen maser, the quietest and most stable frequency standard in existence at the present time. The end users of these low-noise, stable signals typically are located in the cone areas of spacecraft tracking antennas which may be hundreds of meters from the signal source. The distribution system which carries the signal to the antennas is subjected to harsh environmental conditions: extremes of temperature, electromagnetic and radio frequency signals, and vibration. The signal source, a hydrogen maser, is maintained in an environmentally controlled room at the Signal Processing Center (SPC). The problem then is to preserve hydrogen maser stability performance throughout the distribution system.

This paper deals with the impact of environment on the signal distribution system. Efforts have been made to characterize environmental effects and to design the distribution system to minimize the effects of environment on the reference signal. Certain of the radio science experiments such as planetary occultation and gravity wave measurements place stability requirements on the frequency standards of 1.5 parts in 10^{15} at 1000 seconds and 3600 seconds averaging times. The short term stability requirement is 2 parts in 10^{13} at one second. The hydrogen maser is capable of this performance at the source, but to assure that the signal delivered to the antenna

1 This work represents one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract sponsored by the National Aeronautics and Space Administration.

meets requirements, the distribution system must be an order of magnitude superior in performance. The greatest deterrent to meeting these stability requirements is the exposure of distribution components, including cabling, to the temperature variations between the SPC and the antenna cone area.

The design of the reference frequency distribution system described in this paper is based on optical fibers. The measured temperature coefficient of delay (TCD) for one type of optical fiber used in this application is less than 1 part per million per °C as compared with conventional single mode optical fiber with a TCD of approximately 7 parts per million per °C. The optical transmitter used in the distribution assembly is a commercial, single-mode distributed feedback laser diode with integral optical isolator. A companion optical receiver and distribution amplifiers are located in the cone area of the antennas.

TEMPERATURE EFFECTS

The cables which distribute the reference signals to the antennas at Deep Space Station 15 (DSS 15) are exposed to extreme temperature variations. Figure 1 is a plot of surface temperatures at DSS 15 recorded every four hours for the period 11 June 1992 to 14 June 1992. Note the extremes from a low of about 12°C to a high near 55°C with an average ΔT of 35°C. The length of the cable run from the SPC to the base of the antenna is approximately 500 meters. In order to reduce the effects of temperature variation on the cable, the cables are run through ducts which are at a depth of 1.5 meters beneath the earth's surface. The decision to bury the cables at this depth was based on temperature data recorded over an interval of several months.

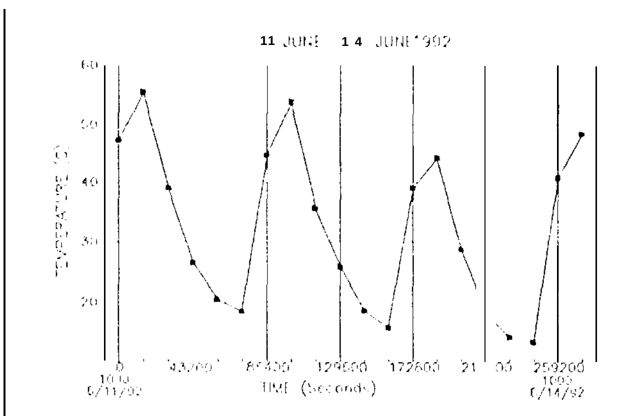

Figure 1. Surface Temperature, DSS 15

The temperature profile of the earth was determined by burying thermocouples at depths of 0.604, 0.906, 1.208, 1.51, and 1.812 meters and employing a data logger with a computer attached to record these data. The results of these measurements are shown in the graph of Figure 2. Measurements were begun on 14 January 1992 and were terminated (by accident) on 26 June 1992. Careful analysis of this data indicates that a cable depth near 60 inches reduces the temperature variations at the cable to meet the required stability at the antenna reference distribution equipment. Note in Figure 2 the line with the larger variations from day to day is the surface temperature averaged over a 24 hour period. For more detail, the same temperature data reduced to the period 1 June 1992 through 26 June 1992 is shown in Figure 3. The ground temperature at a depth of 1.5 meters is shown in Figure 4.

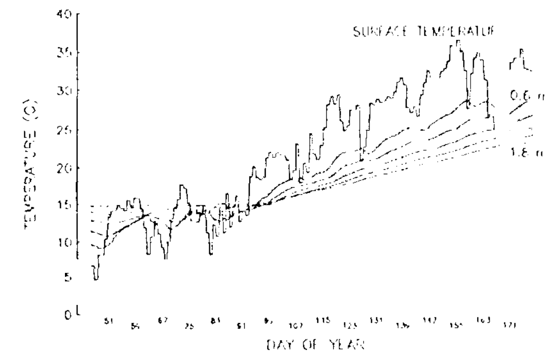

Figure 2. Ground Temperature, DSS 15

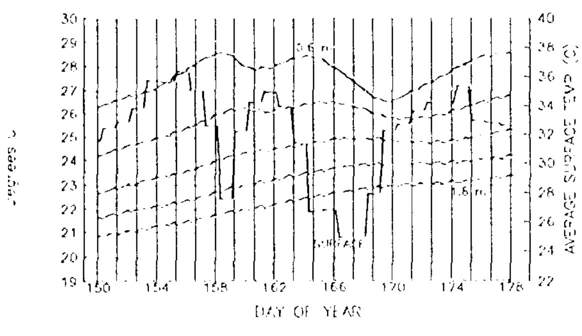

Figure 3. Surface Temperature, DSS 15, 6/1/92 - 6/26/92

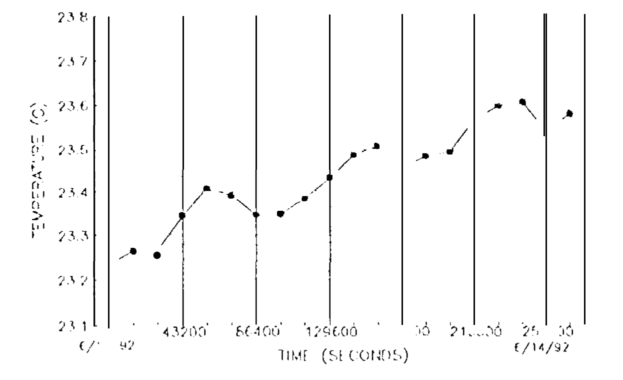

Figure 4. Ground Temperature at 1.5 m Depth, DSS 15

An independent ground temperature study was undertaken at DSS 13 in 1991 with two thermocouples, each buried 1.5 meters. DSS 13 and DSS 15 are separated by a distance of 29 kilometers. The data taken at DSS13 is shown in Figure 5 corroborates the DSS 15 data. Observe the cyclic nature of the temperature at a depth of 1.5 meters in the. Mojave desert

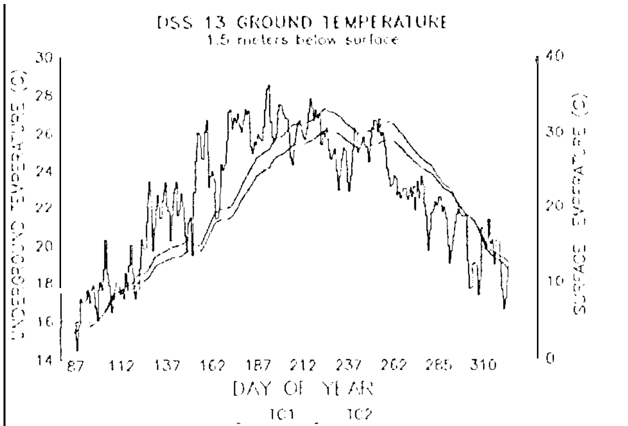

Figure 5. Ground Temperature, DSS 13

A curve-fitting routine was used to determine a temperature versus depth attenuation model. The "best-fit" equation for this model is

$$\Delta T = \Delta T_0 (3.29580982 - 2.47616056 X^{(1/2)})^2$$

where ΔT is the temperature variation at depth x meters and ΔT_0 is the surface temperature variation. Computations show that temperature variations are attenuated by 21 dB at a depth of 0.906 meters, 30 dB at 1.208 meters, and 45 dB at 1.51 meters. An engineering decision was made to bury the cable ducts as near 1.5 meters as possible. Figure 6 is a plot of temperature change as a function of distance beneath the surface of the earth.

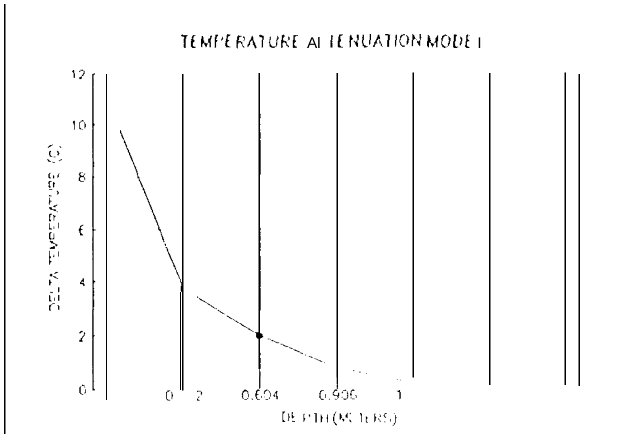

Figure 6. Temperature Change versus Depth of Cable

STABILITY versus TEMPERATURE

With approximately 500 meters of the cable underground at a depth of 1.5 meters, there still remains nearly 50 meters of cable from the base of the antenna to the cone area. This 50 meter run of cable is exposed to extremes of hot desert sun directly on the cable and the low temperature of the night. The mechanics of eliminating temperature varitions on the exposed section of cable render this task unfeasible at the present time. To mitigate the effects of temperature on the exposed cable, a special optical fiber with a low thermal coefficient of delay (LTCD) has been installed. The thermal coefficient of delay for this fiber is less than 1 ppm/°C for temperatures below 35°C.

The signal stability due to the temperature variations over the 50 meters of exposed fiber optic cable is calculated as follows:

$$\Delta\Phi = \Delta L x 360° / \lambda_m$$

$$\Delta L = Lk\Delta T$$

Where $\Delta\Phi$ is the change in phase delay introduced by the temperature variation ΔT, k is the thermal coefficient of delay of the fiber in ppm/°C, L is the optical fiber length in meters, and λ_m is the wavelength of the reference signal in the medium (at 100 MHz in glass, the wavelength is 2.1 m). Calculating the phase change for a 35° C peak-to-peak temperature excursion over a 24 hour period yields a peak-to-peak phase variation of 0.120° at 100 MHz. The calculated fractional frequency variation $\Delta f / f_0$ for 24 hour averaging is $3.8 x 10^{(-17)}$ and at 1000 second averaging times is $2.42 x 10^{(-16)}$. The

1000 second calculation is based on the assumption that the phase variation is a 0.120° peak-to-peak sinusoid with a period of 86,400 seconds. "

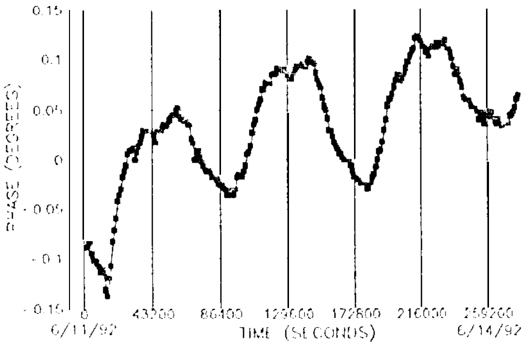

Figure 7. Measured Phase Change, 100 MHz, DSS 15

Phase data for the same time interval was measured using a two-way fiber optic link at DSS 15, thus the data shown in Figure 7 is twice the actual phase deviation. The peak-to-peak phase changes over the uplink fiber are then approximately 0.075°/Day. The error between calculated phase change and measured phase may be attributed to the fact that the temperature was measured at the ground surface but in fact the cable run up the antenna was in shade for a substantial portion of the 24 hour interval which would render less than the 30° peak-to-peak used for estimating the fractional frequency variation.

This measured phase data was used to numerically calculate the Allan deviation for the fiber link [1]. Figure 8 is a plot of Allan Deviation σ versus averaging time τ determined from a numerical analysis of the data of Figure 7. Since the two-way link contributes linearly to the total phase deviation, the Sigma values shown in Figure 7 may be divided by 2 to yield :

$$\sigma \approx 8 x 10^{(-17)} \text{ at } \tau = 1000 \text{ Seconds and}$$

$$\sigma \approx 4 x 10^{(-17)} \text{ at 1 Day Averaging time,}$$

which is more than an order of magnitude lower than radio science system requirements at the present time.

Temperature variations inside the antenna equipment room where the fiber optic terminal hardware is located indicate as great as 2° C peak to peak over a 24 hour period. Temperature control of the most sensitive electronics modules in the receiver reduces ambient temperature changes by a factor of 25, thus the signal stability is not degraded by these temperature changes. At the transmitter end of the fiber optic link, control room temperature is maintained

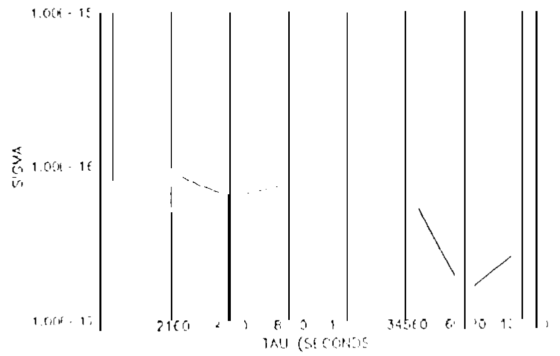

Figure 8. Allan Deviation for Two-way Fiber Optic Link, DSS 15, 11 June 14 June 1992

within 1°C and the laser transmitter has an internal thermoelectric cooler. Therefore, the stability of the reference signal at the antenna is primarily a function of the outside temperature variations and the characteristics of the optical fiber and is affected minimally by the terminal equipment.

OTHER ENVIRONMENTAL EFFECTS

Accelerometers were used to measure vibrations in the antenna near the area of the equipment location [2]. Antenna tracking motion and wind induced vibrations typically are less than 1 mG rms and are confined to frequencies below 15 Hertz. At DSS 15, a very sharp spurious vibration response at 29.5 Hertz has been identified as induced by the air-handlers. The magnitude of this spur can be as great as 16 mG rms. Vibration frequencies of this order of magnitude can cause optical back-reflections which manifest themselves as phase-noise in the laser. To eliminate phase noise caused by back-reflection, an in-line optical isolator has been installed at the output port of the laser. Test results indicate that vibration magnitudes as great as 100 mG have no effect on the laser phase noise performance with the isolator installed [3].

The fiber optic electronics hardware as well as the optical fiber cable have been humidity tested from 10% to 90% relative humidity with no apparent degradation of performance. Atmospheric pressure testing has shown the equipment's phase noise and stability performance to be insensitive to pressure changes.

Radio frequency and magnetic interference can be a source of signal degradation. The optical fibers are immune to both rfi and emi since glass is not an electrical conductor. The receiver and distribution amplifiers at the antenna are enclosed in rfi/emi shielded enclosures to reduce the effects of local fields on the electronics and copper cables, Measurements of the rf reference signal indicate that there are no spurious frequencies present at the output ports of the terminal equipment.

CONCLUSIONS

Stability measurements indicate that the 100 MHz reference frequency signal for radio science experiments meets or exceeds requirements. Environmental temperature effects have been reduced by (1) employing an optical fiber with a very low thermal coefficient of delay, (2) running the fiber cable underground ducts at a depth of five feet, and (3) providing thermoelectric temperature control for the terminal equipment. Vibration induced optical back-reflections effects are minimized by using optical isolators in-line with the laser transmitter. Interference due to stray radio frequencies and magnetic fields are minimized by shielding the electronics and by employing optical fibers as the transmission medium.

To date, fiber optic distribution for reference frequencies has been installed and tested successfully at three NASA/JPL 34 meter antenna sites. Three more installations are to be completed at the 70 meter tracking antennas by the Fall of 1993.

REFERENCES

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3. P. White, M. Calhoun, and P. Kuhnle, "Fiber-optic Distribution of Ultra-stable Timing Signals for JPL's Deep Space Network", Proceedings of IEEE Southeastcon '90, New Orleans, LA, May 1990.

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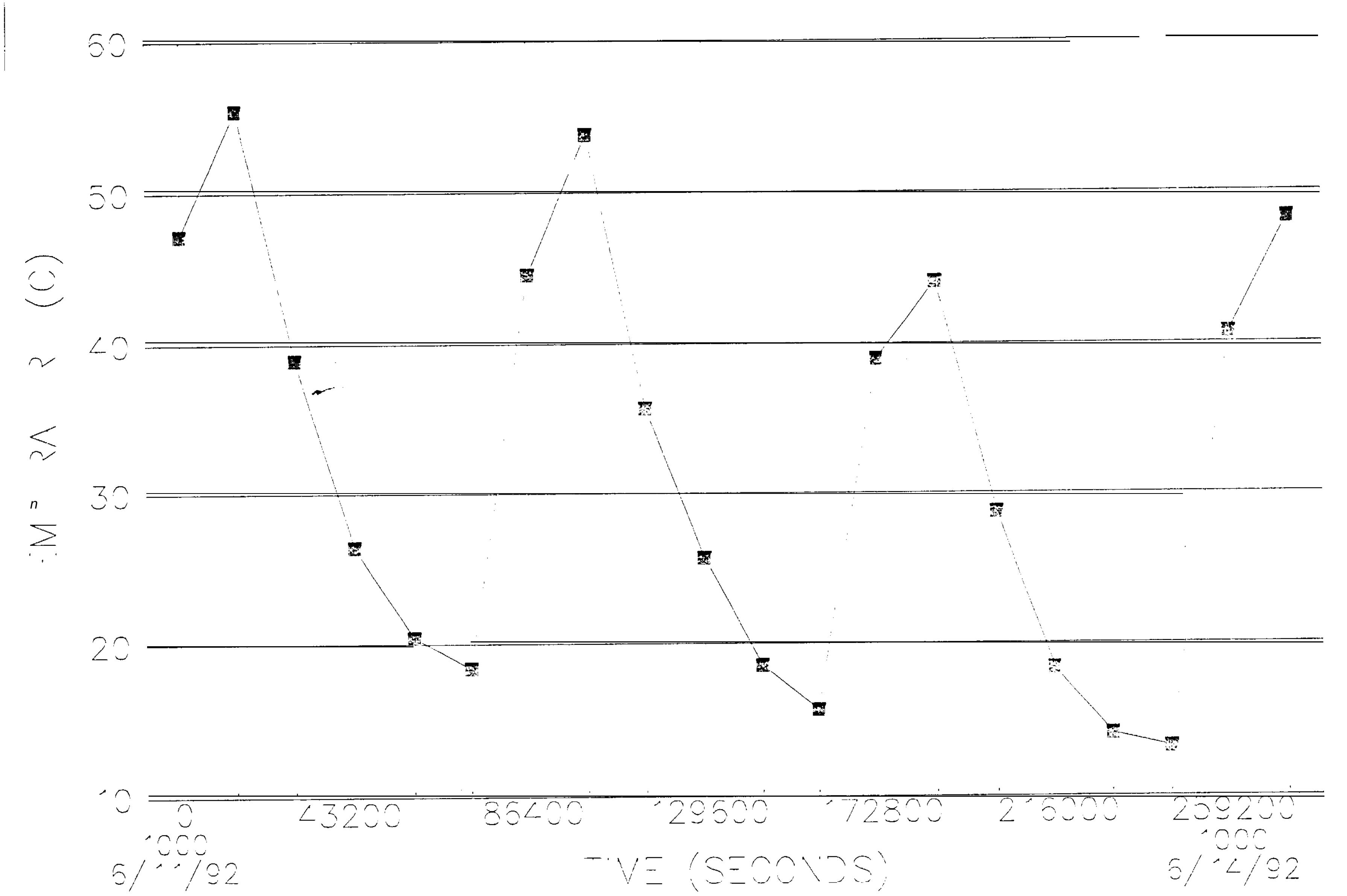
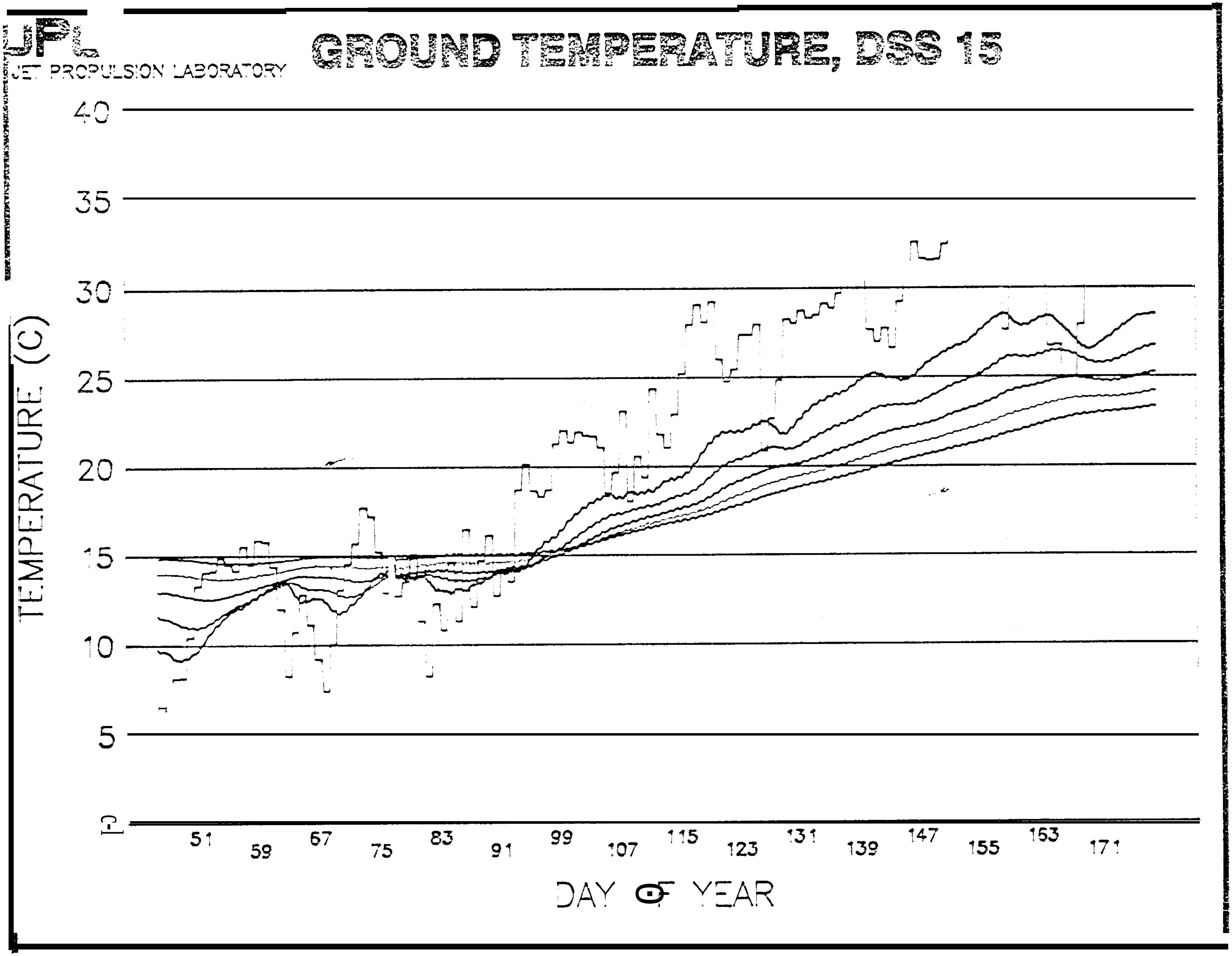
OBJECTIVES

- TEST AND CHARACTERIZE ENVIRONMENTAL EFFECTS AT THE NASA/JPL DEEP SPACE STATIONS
- DESIGN AND IMPLEMENT A DISTRIBUTION SYSTEM TO FUNCTION IN A HARSH ENVIRONMENT
- PROVIDE SUPPORT FOR RADIO SCIENCE EXPERIMENTS IN THE NASA/JPL DEEP SPACE NETWORK
- PROVIDE NOISE-FREE, HIGH PHASE STABILITY REFERENCE FREQUENCY TO THE DEEP SPACE STATION ANTENNA

SURFACE TEMPERATURE, DSS 15

11 JUNE–14 JUNE 1992

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GROUND TEMPERATURE, DSS 15
TEMPERATURE (C)
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DAY OF YEAR

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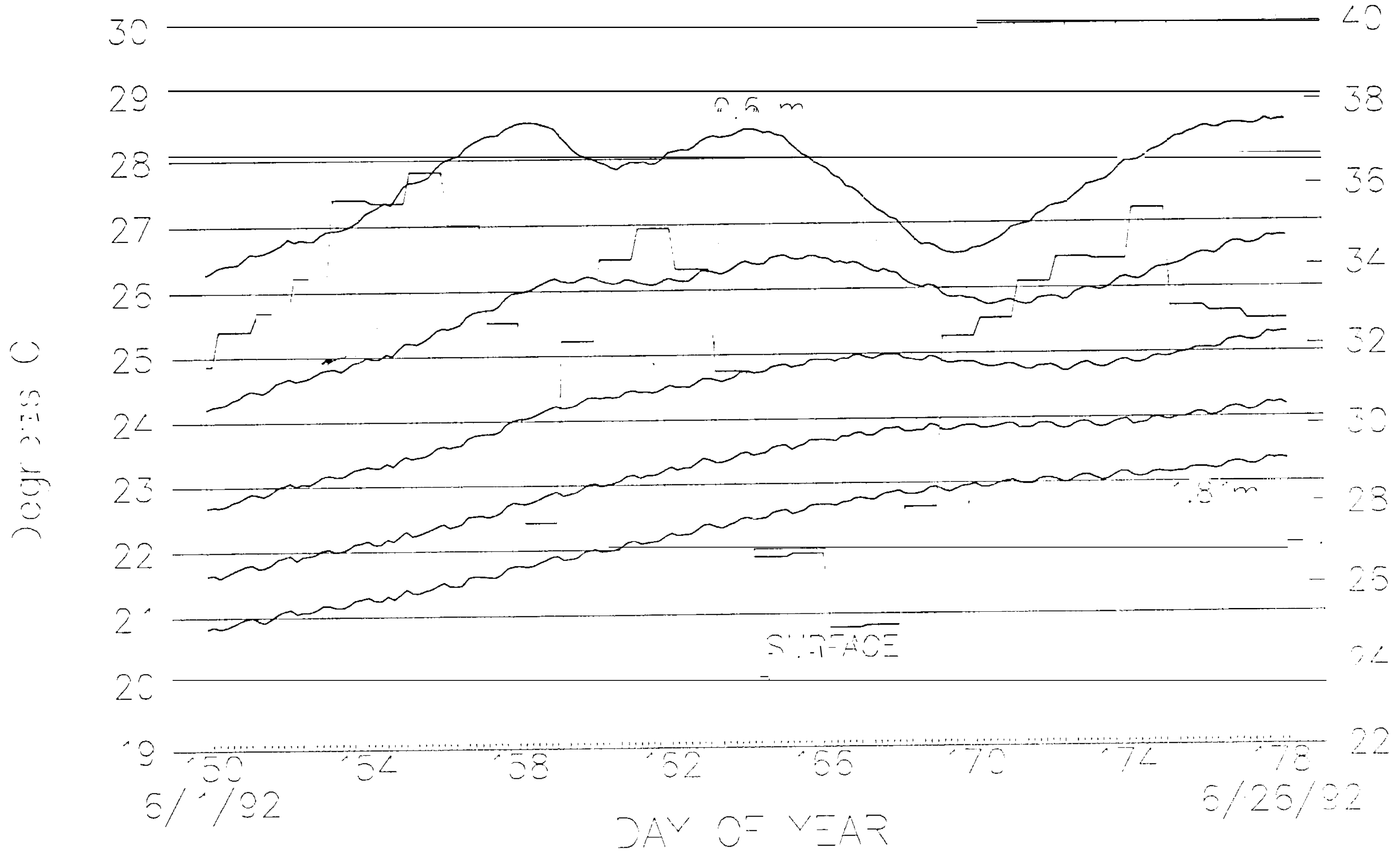
GROUND TEMPERATURE, DSS 15



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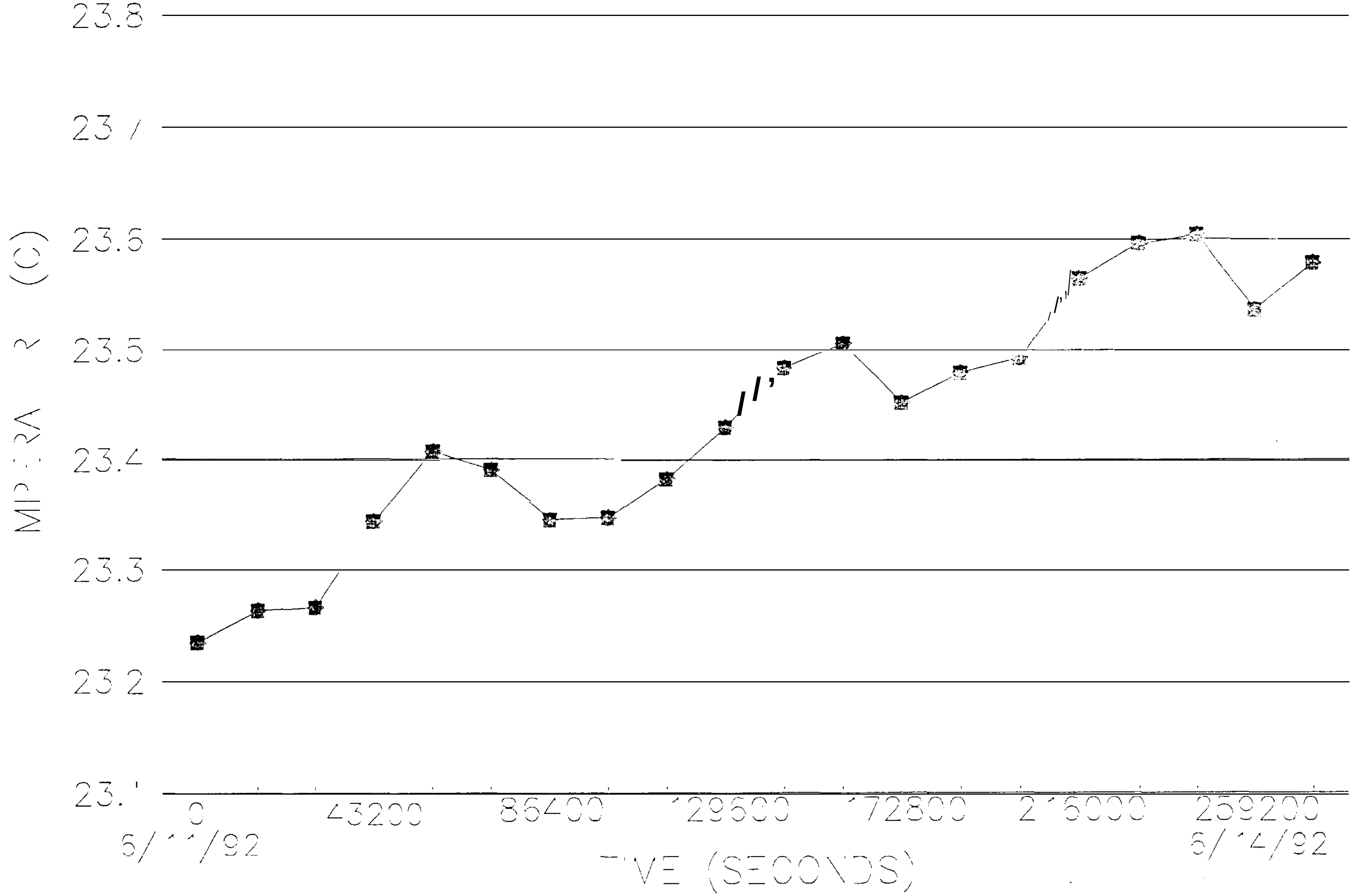
GROUND TEMPERATURE AT 1.5 m DEPTH, DSS 15



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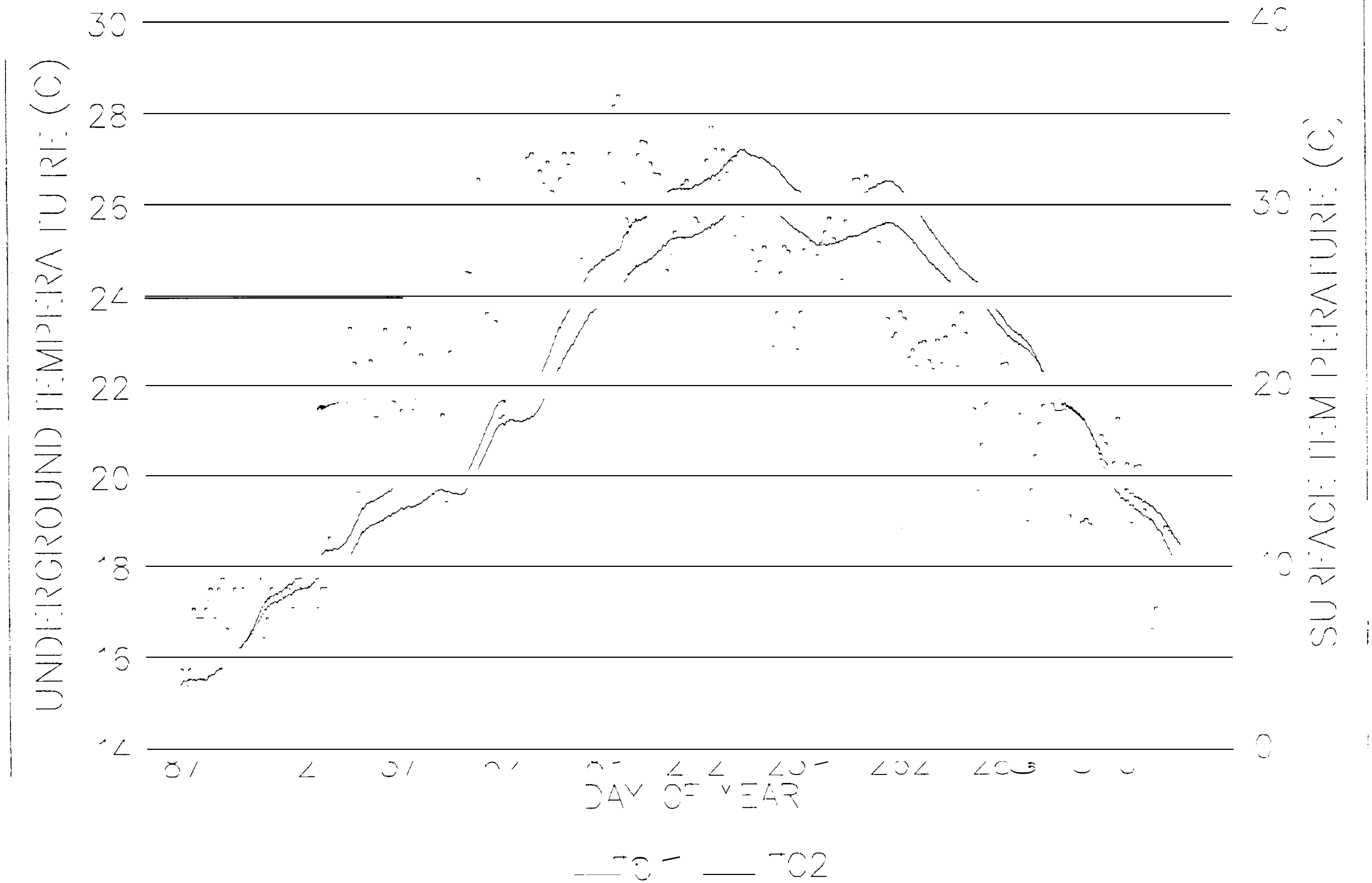
DSS 13 GROUND TEMPERATURE

1.5 METERS BELOW SURFACE



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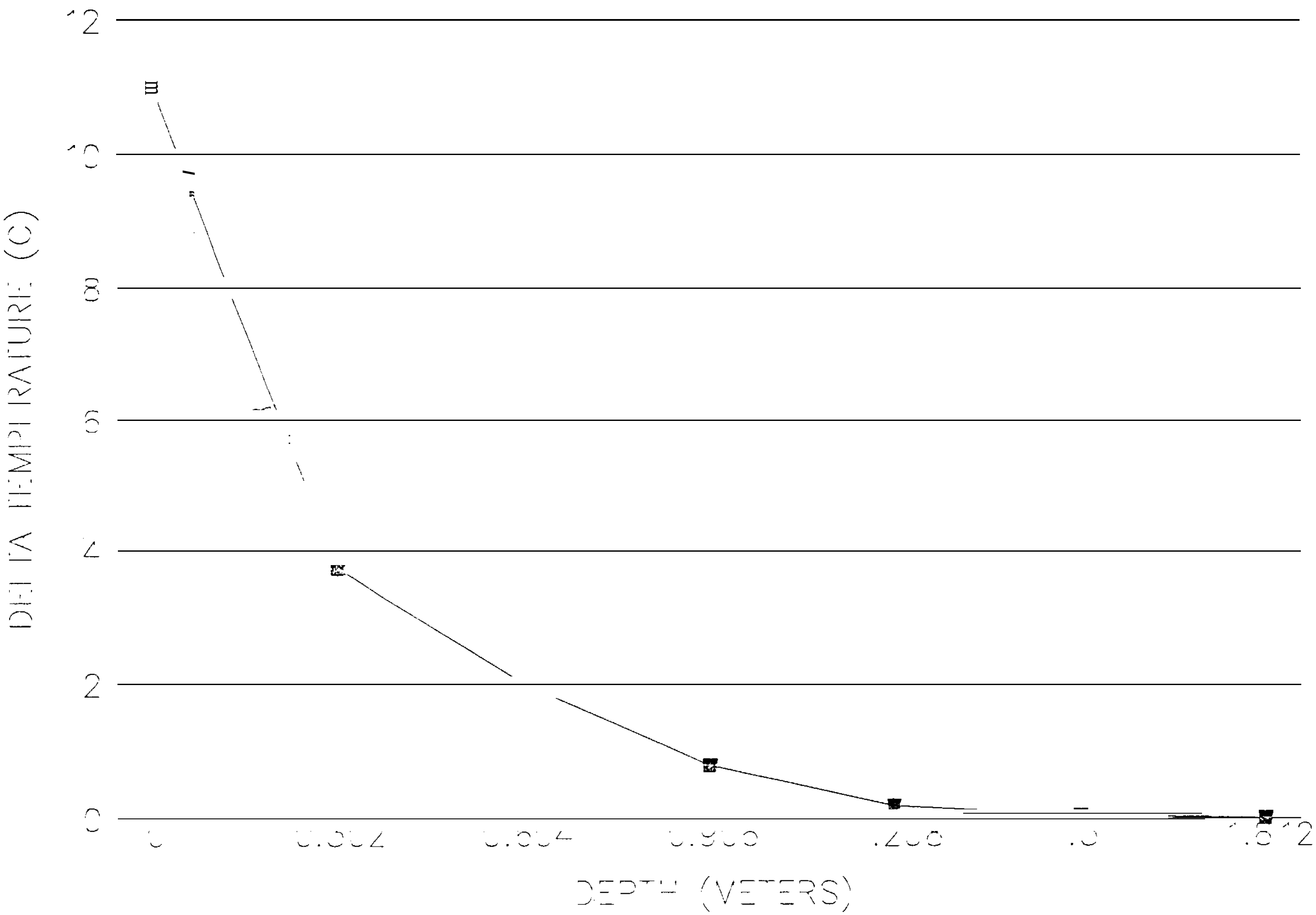
TEMPERATURE ATTENUATION MODEL



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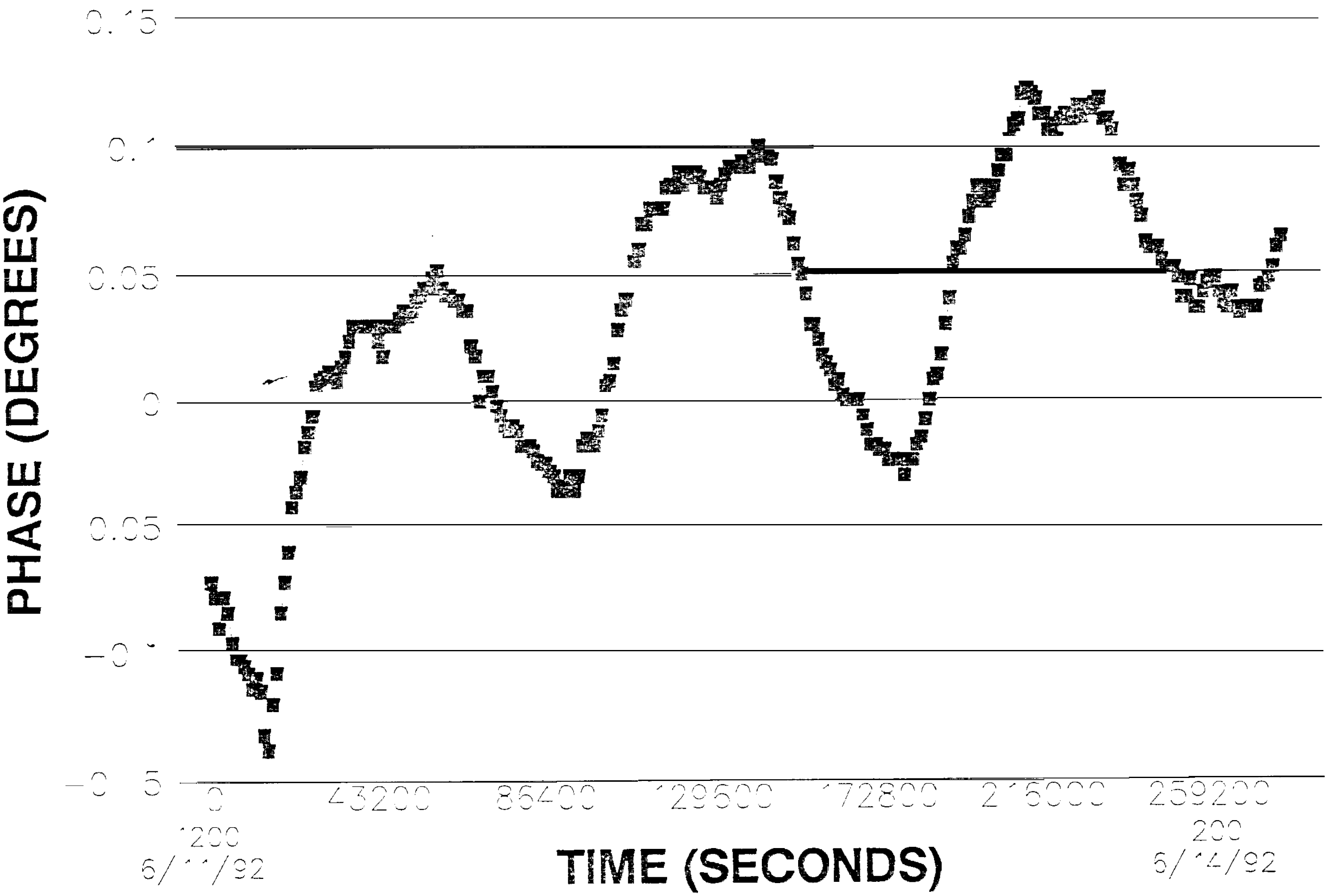
PHASE VARIATIONS, DSS 15
FIBER OPTIC LINK, 100 MHz



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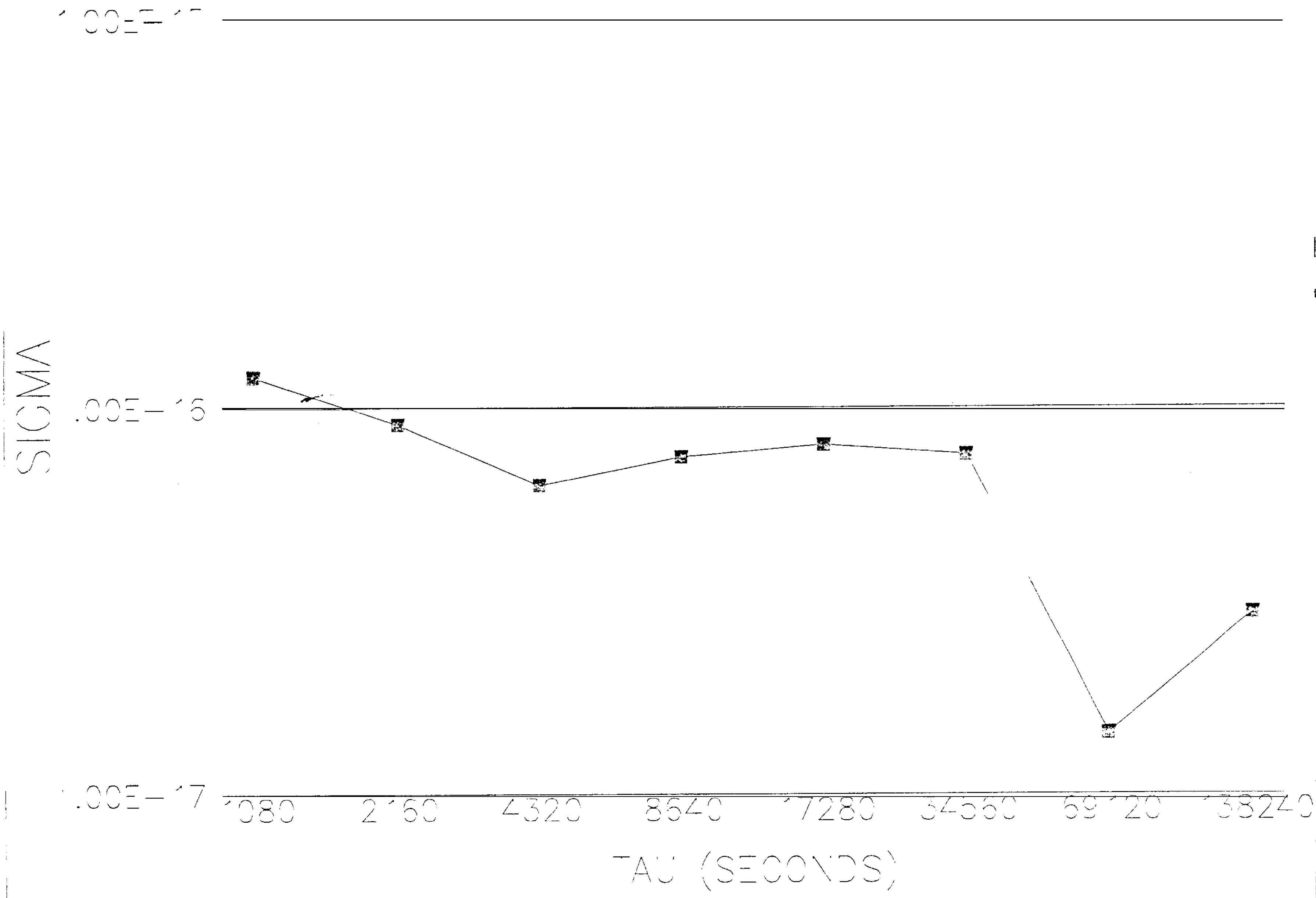

SUMMARY

- TEMPERATURE VERSUS DEPTH MODEL DETERMINED BASED ON DATA TAKEN AT THE NASA/JPL DEEP SPACE STATIONS
- DETERMINED VIBRATION CHARACTERISTICS AND TEMPERATURE INSIDE THE ANTENNA EQUIPMENT ROOM
- DESIGNED, NSTALLED, AND TESTED A DISTRIBUTION SYSTEM WHICH PROVIDES NOISE-FREE, HIGH PHASE STABILITY REFERENCE FREQUENCY TO THE DEEP SPACE STATION ANTENNAS
- HYDROGEN MASER PERFORMANCE IS NOT DEGRADED BY THE DISTRIBUTION SYSTEM
- RADIO SCIENCE STABILITY AND NOISE REQUIREMENTS ARE MET